A New Approach for Exploring Ice Sheets and Sub-Ice Geology

Active seismic measurements were an important part of geophysical traverses on the Antarctic ice sheet as far back as the 1920s. These methods lost their leading role for ice thickness measurements to much faster ground-based and airborne radar surveys because of the considerable logistical effort needed for seismic data acquisition. However, new achievements with a vibrator source in active seismics (vibrators for short) could open up new prospects and foster future geological and glaciological surveys in Antarctica and Greenland on ice caps and glaciers.

Active seismic methods have the unique ability to image sub-ice geology and remotely obtain its physical properties. Friction at the basal interface of an ice sheet plays a pivotal role in controlling ice dynamics and is largely determined by the presence of water and/or sediments underneath the ice. High-quality seismic reflection measurements come in demand as scientific interest in the dynamics of ice streams (e.g., West Antarctic ice streams) increased and as site surveys were needed for optimum sampling of sub-ice sediments for palaeostratigraphic studies (e.g., Cape Roberts Project, Antarctic Geotopical Drilling (ANDRILL)). Nevertheless, the available literature demonstrates that seismic studies on ice sheets are not widespread and are only carried out on small, local scales over a few tens of kilometers. Prominent examples of such seismic studies are the observation of transient processes in bed geology driven by ice flow (Smith et al., 2007) and the long record of seismic exploration of ice shelves over time (e.g., for example, around Lake Vostok and more recently around subglacial Lake Ellsworth. Seismic properties of the ice sheets remain an only occasional topic (Rongen et al., 2008), often complementary to radar imaging.

The Firn-Layer Problem

The upper tens of meters of an ice sheet consist of a highly porous layer of firn (snow that is more than 1 year old), which acts as an acoustic waveguide, or trap, making the excitation of seismic waves from a surface source difficult. Soft firn causes large elastic energy losses for impulsive sources. During most seismic surveys in Antarctica, researchers have used explosives in 10- to 20-meter deep boreholes to overcome signal attenuation caused by the steep velocity gradient in the surface layer between soft firn and harder ice. The boreholes are drilled by different techniques, requiring considerable time and energy by each drill. With the seismic source below the surface, surface ghost reflections are commonly present in the data. Despite these difficulties, explosive sources in shallow boreholes are still the simplest way to obtain acceptable data quality. Even with this approach, involving minimal efforts, the necessary logistical requirements have discouraged the acquisition of longer seismic profiles, for example, as part of overland traverses.

The Vibroseis Source

During the 2009–2010 Antarctic field season the Linking Micro-Physical Properties to Macro Features in Ice Sheets With Geophysical Techniques (LIMPICS) project aimed to make seismic vibrator measurements for the first time in Antarctica (Kristoffersen et al., 2010). In contrast to an impulsive surface source of milliseconds duration, a controlled vibrator source emits energy as a finite amplitude pressure pulse over many seconds. Energy losses by inelastic behavior are thus much less because of reduced ground pressure. The project used a truck-mounted Failing Y-4100 vibrator (peak actuator force was about 12 tons) on skis towed by a Pistenbully snowcat on the floating Ekström Ice Shelf near the German research station Neumayer III. Sweeps of 10-second duration with a linear increase in frequency over the range of 10–100 hertz were compared to shots of 300 gram explosive charge fired in 15-meter deep boreholes (Figure 1). Both types of data were recorded with a snow streamer (i.e., geophones towed on a cable over the snow surface), and the data show the primary reflection from the ice-water interface, its multiples, and the reflections from and within the seafloor. The explosive sources are clearly rich in higher frequencies (up to 300 hertz), while the energy in the Vibroseis record is limited to the sweep frequencies. The vibrator excites slightly more surface waves than the explosive charge, but the total energy level is higher relative to explosive charge at 10-meter depth. Identifiable reflections are present over a two-way travel time of more than 2 seconds.

With the current vibroseis–snow streamer setup, seismic data production is about 10 kilometers per day for single-fold coverage, with peak production rates up to 3 kilometers per hour. Optimization should enable doubling of the production rate to 20 kilometers per day even for multifold coverage, comparable to onshore vibroseis surveys. Surface properties do not impose a problem, as the vibrator pad (2.5 square meters) generally sank no more than a total of 10–20 centimeters in dry snow after three consecutive sweeps.

Future Prospects

A vibrator has the advantage of being a known and repeatable source signal and is less prone to the superposition of energy from other wavefields, for example, from the multiple reflections. This is of great advantage for the Vibroseis source over the explosive charge in terms of cost efficiency. Further improvements in Vibroseis technology are necessary, however, to fully exploit the potential of the Vibroseis method. A more powerful source is necessary to penetrate thicker ice sheets and to execute a complete survey. New Vibroseis machines with higher energy output are currently being developed, and some are already in use. The Vibroseis source is clearly rich in higher frequencies, and its multiples, and the reflections from and within the seafloor. The explosive sources are rich in higher frequencies (up to 300 hertz), while the energy in the Vibroseis record is limited to the sweep frequencies. The vibrator excites slightly more surface waves than the explosive charge, but the total energy level is higher relative to explosive charge at 10-meter depth. Identifiable reflections are present over a twoway travel time of more than 2 seconds.

Global Shallow-Water Bathymetry From Satellite Ocean Color Data

Knowledge of ocean bathymetry is important, not only for navigation but also for scientific studies of the ocean’s volume, ecol- ogy, and circulation, all of which are related to Earth’s climate. In coastal regions, moreover, detailed bathymetric maps are critical for storm surge modeling, marine power plant planning, understanding of ecosys- tem connectivity, coastal management, and change analyses. Because ocean areas are enormously large and ship surveys have limited coverage, adequate bathymetric data are still lacking throughout the global ocean.

Satellite altimetry can produce reasonable estimates of bathymetry for the deep ocean [Sandwell et al., 2003, 2006], but the spatial resolution is very coarse (~6–9 kilome- ters) and can be highly inaccurate in shallow waters, where gravitational effects are small. For example, depths retrieved from the widely used ETOP02 bathymetry database (the National Geophysical Data Center’s 5-minute global relief data, http://rsd01.ngdc.noaa.gov/mgg/fi/er1084.html) for the Great Bahama Bank (Figure 1a) are systematically in error when compared with ship surveys [Bennett et al., 2001] (see Figure 2b). No statistical correlation was found between the bathymetry measurements, and the root-mean-square error of ETOP02 bathymetry was as high as 208 meters. Yet determining a higher spatial resolution (~60 meters) on the Great Banks (Figure 1b) is only marginally better (i.e., 12–15 meters). As such, ETOP02 bathymetry of this region with ship surveys would require a few years of nonstop effort.

Clearly, alternative methods are needed for estimating bathymetry in shallow coastal regions. A rapid and relatively robust method may be developed through a new way of looking at satellite measurements of ocean color. This takes advantage of the fact that photons hitting the shallow ocean bottom and reflecting back to the surface modify the appearance of ocean color.

Retrieving Depth From Analyzing Spectral Data

It is well known that measurements of water color could help define bathymetry in shallow regions [Lyzenga, 1981; Pak et al., 1979]. Earlier methods to estimate bathymetry from ocean color, however, were limited to approaches [Lyzenga, 1981; Pak et al., 1979, 1983] that required a few known depths to develop an empirical relationship, which then allows researchers to convert multiband color images to a bathymetric map. The resulting empirical relationships are generally sensor and site specific [Dier- sen et al., 2003, Stumpf et al., 2003] and not transferable to other images or areas. Further, the approach is not applicable for regions difficult to reach, due to lack of in situ calibration data.

To overcome such a limitation, a physics- based approach, called hyperspectral optimi- zation process exemplar (HOPE), has been developed [Lee et al., 1999]. Basically, the spectral reflectance (Rs) of water leaves a unique fingerprint on the ocean surface (Figure 1a) and can be modeled as a function of five independent variables that include bottom depth, sediment reflectance, the ratio of seawater leaving irradiance to direct irradiance hitting the sea surface) is modeled as a function of five independent vari- ables that include bottom depth, sediment reflectance, and ocean color. This takes advantage of the fact that photons hitting the shallow ocean bottom and reflecting back to the surface modify the appearance of ocean color.

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also of having reduced logistics costs, higher production rates, and less impact on the environment than explosives. Further investigations should address appropriate selection of vibrator site (commercially available vibrators range from 50 kilograms to more than 10 tons) for a trade-off between resolution and penetration depth depending on target objectives and the applicability of vibrator types (reducing shear or surface waves) to sophisticated analysis methods such as amplitude variation with offset. Logistical limitations require improved implementations such as mounting a vibrator directly on a sled (instead of on a truck on skids) and modular systems for deployment with smaller airplanes. The vibrators/snow streamer configuration used presented a tool suitable for traverses of several hundred kilometers and thus for target-oriented surveys for specific objectives such as (1) exploring the sub-ice sediment structure suitable for sampling by scientific drilling and analysis for climate information, (2) investigating the physical properties of the ice-bedrock interface, (3) exploiting ground-penetrating processes like internal basal ice structures and water-routing systems, (4) conducting surveys of subglacial lake settings, especially water depth and sediment information, (5) complementing radar in exploring the physical properties of the lower part of the ice sheet; and (6) tying together offshore and onshore seismic data for geological interpretation.

Photos of the vibrator truck and the measurement setup are available in the online supplement to this Eos issue (http://www.agu.org/eos/elec/).

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References


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Application of the New Method

The HOPF method was applied to ocean color images of the Great Bahama Bank collected by the Medium-Resolution Imaging Spectrometer (MERIS) operated by the European Space Agency (ESA). The data collected 14 December 2004 by MERIS were led to HOPF to derive properties of the water column and bottom. The derived bottom depth (no tidal correction is presented in Figure 1c) shows a range of about 1–3 meters across the main portions of the banks and a maximum depth of about 20 meters at the bank edge. MERIS-derived depths were compared with ship surveys [Vanniere et al., 2009], and it was found that the two data sets were highly statistically correlated, with a root-mean-square error of MERIS-derived bathymetry of around 3.4 meters (Figure 15). Note that the errors factor in the ambiguity that results from differences in the spatial scale of the relative measurements (300 meters for MERIS and 40 meters for ship, and the spatial heterogeneity in bathymetry over those scales.

Results from another MERIS measurement (6 September 2008) show similar accuracy (see Figure 14, indicating that this approach is robust and repeatable. Although an error of around 3 meters cautions against the use of these data for navigation, the retrieval bathymetry is substantially more reliable than that presented in ETP02.

Toward More Accurate Global Assessment of Shallow Waters

Because polar-orbiting sensors like MERIS and Moderate Resolution Imaging Spectroradiometer (MODIS) make measurements globally and near daily with a spatial resolution of hundreds of meters, the proof of concept seen through comparing remote sensing retrievals with ship surveys around the Great Bahama Bank demonstrates the great potential of retrieving global, high-resolution, shallow-water bathymetry from ocean color satellites. Such retrievals can complement information gained from satellite surveys and altimetry retrievals. Merging such data products with other bathymetry sources will provide unprecedentedly valuable information to scientists, commercial entities, coastal managers, and decision makers. To reach this highly desired goal, however, would require dedicated efforts to improve and mature algorithms for processing optically shallow waters from current and future ocean color satellite measurements.

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